

## Are changes in N:P ratios in coastal waters the key to increased red tide blooms?

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### Abstract

There is mounting evidence of a global increase in nutrient levels of coastal waters through riverine and sewage inputs, and in both the numbers and frequency (as well as the species composition) of red tides. However, it is still not possible to conclude the extent to which the increase in red tides in coastal waters can be attributed to the increase in nutrient levels, since so many other factors are involved.

Undoubtedly, a relationship exists between red tides and the N and P load of coastal waters, and many nutrient enrichment experiments have shown that marine phytoplankton blooms are often nutrient limited. What is now becoming clear, however, is that although in classical Liebigian terms minimum amounts can be limiting, nutrient ratios (such as N:P and Si:P) are far more important regulators.

This paper reviews evidence collected by the authors from Tolo Harbour, Hong Kong together with data collected in Japanese and North European coastal waters by various authors, which indicates that both long term and relatively short term changes in the N:P ratio are accompanied by increased blooms of non-siliceous phytoplankton groups and, furthermore, that the growth of most red tide causative organisms in Hong Kong coastal water is optimized at a low N:P (atomic) ratio of between 6 and 15.

### Introduction

So long as growth is not overprolific, algal blooms are of benefit to both natural fisheries and marine culture operations since the animals' food supply is plentiful. Sometimes, however, the algae occur in such large numbers that they colour the sea surface. The best known are the red tides which result, though others like brown tides can also occur depending on the algae involved. Such blooms may have a negative effect and cause economic losses to fisheries and aquaculture and, indeed, they may have impacts on human health. Sometimes, the fish kills which result from these harmful algal blooms are simply a result of the pure numbers of algae involved, when high algal respiration or high bacterial decomposition of the bloom lead to oxygen depletion. On other occasions, however, the algae have the ability to produce toxins which can kill fish or find their way through fish or shellfish to humans, resulting

in various kinds of poisoning. Another type of harmful algal bloom (often termed noxious algal blooms) involves the algae damaging the fishes gills, and this can lead to severe losses in cage fish.

Algal blooms are natural phenomena, which have occurred throughout recorded history. However, in the past few decades there has been mounting evidence from around the world to suggest that coastal marine phytoplankton blooms have increased in frequency, intensity and geographic distribution. For example, at Halskov Rev (Nielsen & Aertebjerg, 1984; Gargas et al., 1980); in the Gulf of Finland (Niemi, 1974); in the Baltic Sea (Nehring et al., 1984; Renk et al., 1988); in Dutch Coastal waters (Cadée, 1986b); along South African coasts (Horstman, 1981); in Tolo Harbour, Hong Kong (Lam & Ho, 1989); and in Chinese coastal waters (Qi et al., 1995). Ho & Hodgkiss (1991) in a review of red tides in subtropical coastal waters from 1928 to 1989 showed that the number of recorded

occurrences had escalated from 1 or 2 every 10 years at the beginning of this period to over 220 between 1980 and 1989; and that 19 countries in the subtropical region were now badly affected.

Reviewing the evidence available, Anderson (1989) concluded that there had been 'a major global expansion ..... of red tides throughout the world' and Smayda (1990) referred to a 'global epidemic of algal blooms'.

Smayda & White (1990) argued that there were not enough long term data at the global level to conclude with certainty that toxic and noxious algal blooms have been increasing in frequency and intensity over the past 20 years, and Smayda (1990) challenged the view that a global bloom epidemic is currently occurring on the grounds that it may be merely an artifact of increased monitoring, improved analytical techniques or increased awareness of toxic outbreaks accompanying increased mariculture of finfish and shellfish. However, amongst the data sets now available, there is clear evidence of a long term increase in phytoplankton blooms and red tides in many coastal waters. Even Smayda (1990) noted that there was considerable evidence to suggest that significant changes in phytoplankton species occurrences, biomass and productivity, novel species occurrences, unusual blooms, and shifts in predominance have occurred in regions of the world as far apart as the North Sea, South Africa and Hong Kong. He concluded that, at least, 'a potential for global expansion of algal bloom problems is now occurring'.

It is clear that we need to better understand such algal blooms so that we might be able to prevent their occurrence, reduce their damaging effects or, at least, be able to predict when and where they might occur.

Hallegraeff (1993) has explored four explanations for the apparent global increase in algal blooms, namely: increased scientific awareness; increased utilization of coastal waters for aquaculture; transport of dinoflagellate cysts in ships' ballast waters or associated with shellfish imports; and stimulation of plankton blooms by 'cultural eutrophication' and/or unusual climatological conditions. He concludes that it may not be possible, for some time, to have a conclusive answer regarding the relative importance of each of these, but that nutrient loading has an obvious relationship with increased blooms.

Since we have no further data to add to those which Hallegraeff (1993) reported regarding his first three 'explanations' and, since he himself highlights the obvious and important relationship between nutrient loading and increased blooms, we have turned

our attention to the possible stimulation of plankton blooms by eutrophication. This review explores, therefore, the mounting evidence for an increased frequency, intensity and geographic distribution of such coastal phytoplankton blooms – the so called 'global spread'; looks at the evidence for nutrient loading being related to these increased coastal blooms; and investigates the possibility of a nutrient ratio linkage with algal blooms (rather than simply a Liebigian link between increased nutrient supply and increased blooms).

### **Nutrient loading, nutrient ratios and algal blooms in Hong Kong coastal waters**

There is general agreement that nutrient loads have been increasing in many coastal waters, usually as a result of increased riverine or sewage inputs. For example in the USA, Smith et al. (1987); in the Dutch Wadden Sea (Fransj, 1986); in the Seto Sea, Japan (Okaichi, 1989); in the Baltic Sea (Fonselius, 1972; Nehring, 1984; Niemi & Aström, 1987; Kononen, 1988); and in Tolo Harbour (Hodgkiss & Chan, 1987; Lam & Ho, 1989).

Smayda (1989) points out that there is a general consensus that phytoplankton growth in the sea is often nutrient limited; that the uptake of nutrients such as N, P and Si follow the Redfield Ratio (that is, they exhibit a stoichiometric proportionality); and that numerous nutrient enrichment experiments have shown that nutrient addition tends to relax nutrient limitation.

In Tolo Harbour, Hong Kong, a 10 fold increase in mean dissolved phosphate levels and a 5 fold increase in mean dissolved nitrate levels between 1978 and 1985 coincided with a very large increase in standing crop of phytoplankton ( $\times 8.5$ ), an increase in red tide blooms from 2 in 1977/78 to 17 in 1984 and an increased contribution of dinoflagellate abundance from 26 to 66% of the phytoplankton population in the outer harbour and from 11 to 26% in the inner harbour (Chan & Hodgkiss, 1987; Hodgkiss & Chan, 1983, 1986, 1987). Lam & Ho (1989) showed that an 8 fold increase in red tides in Tolo Harbour between 1976 and 1986 was related to a 6 fold increase in the catchment population, which had brought about a 2.5 fold increase in nutrient loading.

Chiu, Hodgkiss & Chan (1994) studied a relatively unspoilt area of Hong Kong (Tai Tam Bay) and found that, compared to their earlier study (Chan, Chiu & Hodgkiss, 1991), there had been an increase in algal biomass from 1987 to 1991; a small shift in community dominance (diatoms fell from 98.7 to 96.5% of the

Table 1. Optimal N:P (atomic) ratios for the growth of various red tide causative organisms.

Causative Species	Optimal N:P Ratio for Growth
<i>Alexandrium catenella</i> (Whedon & Kofoid) Balech	15–30:1
<i>Ceratium furca</i> (Ehrenberg) Claparède & Lachmann	12–22:1
<i>Gonyaulax polygramma</i> Stein	4–8:1
<i>Gymnodinium nagasakiense</i> Takayama & Adachi	11–16:1
<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy	8–14:1
<i>Prorocentrum dentatum</i> Stein	6–13:1
<i>Prorocentrum minimum</i> (Pavillard) Schiller	4–13:1
<i>Prorocentrum sigmoides</i> Bohm	4–15:1
<i>Prorocentrum triestinum</i> Schiller	8–15:1
<i>Scrippsiella trochoidea</i> (Stein) Balech	6–13:1
<i>Skeletonema costatum</i> (Greville) Cleve	15–30:1

population and dinoflagellates rose from 1.2 to 3.4%); and also a small shift in nutrient loading.

The classical approach to explain such nutrient regulation of marine phytoplankton growth has been based upon Liebig's Law of the Minimum. However, it is now becoming clear that nutrient ratios can be far more important regulators, particularly in terms of species selection. Numerous investigators have superficially looked at the N:P ratio in their attempts to answer the question as to whether N or P was the more limiting nutrient. This use of the Redfield Ratio has been very successful. However, it is now clear that a more important question is whether altered nutrient ratios accompanying eutrophication of coastal waters are an important factor in the increased blooming of some species.

In Hong Kong, data from the Environmental Protection Department for 1984–1990 (Figure 1) indicate that when dissolved N levels were greater than 0.1 mg l<sup>-1</sup> and dissolved P levels greater than 0.02 mg l<sup>-1</sup>, red tide occurrences were highly probable.

Hodgkiss & Chan (1987) and Chan & Hodgkiss (1987) reported a decline in N:P ratio in Tolo Harbour, Hong Kong and, at the same time, a change in the phytoplankton community, with the red tide causative organisms (mainly dinoflagellates) taking over dominance from the diatoms. Thus, in inner Tolo Harbour, changes in the species composition of the phytoplankton from 1981 to 1990 (Table 2) reflected this change in the harbour's phytoplankton community as the N:P ratio declined from an annual mean of around 20:1 to 11:1 during the period 1982 to 1989 (Figure 2).

Environmental Protection Department data also show that with this gradual decrease in the N:P ratio there is a significant increase in red tide occur-

rences during this time period (Figure 2). Regression analysis of this data, which yielded an F value of 0.35 (P=0.583), showed the significant relationship between the two. Interestingly, from this same figure, it can also be seen that whenever a small drop in the N:P ratio occurs, the red tide occurrences increased correspondingly.

In the 1980s, this harbour was seriously affected by red tides and the major species were *Prorocentrum micans* Ehrenberg, *P. sigmoides* Bohm and *P. triestinum* Schiller (Ho & Hodgkiss, 1995). Bottle test bioassay of limiting factors indicated that favourable N:P atomic ratios for these 3 species were 5–10; 4–15 and 8–15:1 respectively. The N:P ratio in Tolo Harbour fell from a mean of 20.3:1 in 1983 to 11.05:1 in 1989 (Figure 2 applies) as these species increased in abundance.

Ho & Hodgkiss (1993) had previously demonstrated that the growth of most Hong Kong red tide causative organisms was optimized at a low N:P (atomic) ratio of between 4 and 16 (Table 1).

## Discussion

Evidence is accumulating from all over the world (not just Hong Kong) that 'accelerated eutrophication' (i.e. the speeding up of this natural process by man's input of domestic, agricultural and industrial wastes) can stimulate algal growth in coastal waters. Thus, in the Gulf of Finland, Niemi (1974) was able to correlate increasing concentrations of phosphorus in the surface layer with increasing annual primary production rates; and Lassig et al. (1978) showed a similar strong positive correlation between these factors. Cadée (1984,

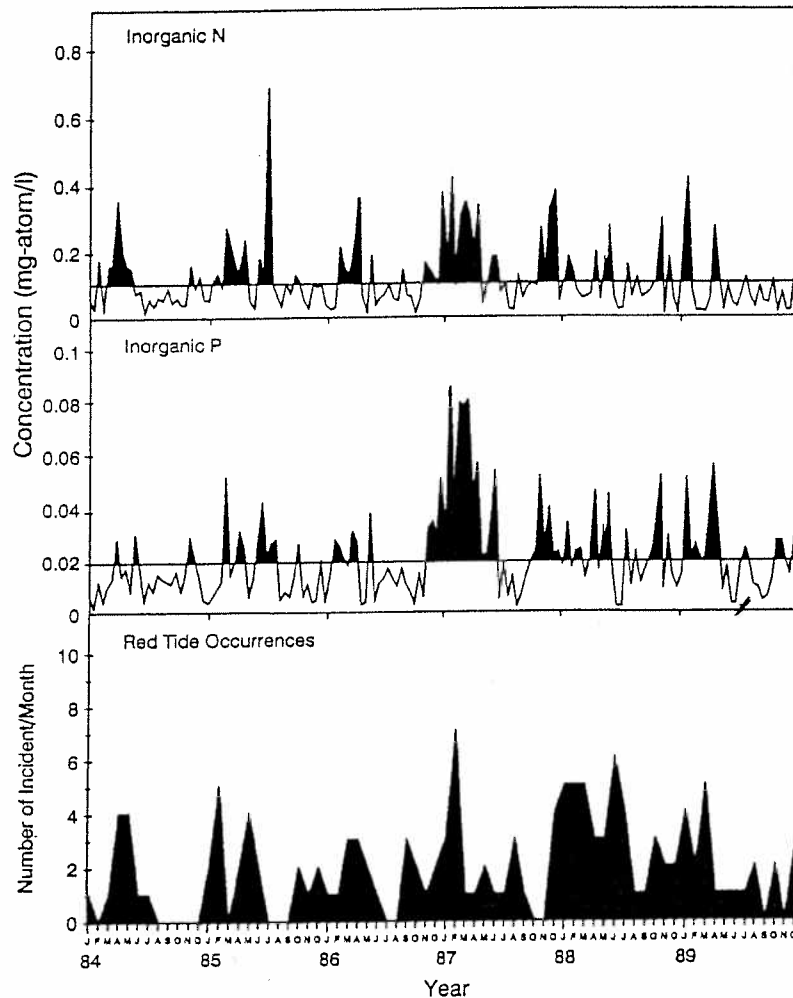


Figure 1. Variations in surface inorganic N and inorganic P concentrations in relation to red tide occurrences in inner Tolo Harbour for the years 1984–1989. (Original data courtesy of the Director, Environmental Protection Department, Government of Hong Kong).

1986a) showed that in the Dutch Wadden Sea (part of the southern North Sea) primary production and phosphate concentrations had both exhibited long term increases. Qi et al. (1995) linked dramatic red tide increases in Chinese coastal waters between 1980 and 1991 with increased nitrate and phosphate levels. In the Black Sea, long term (1957–1984) coincident increases in mean phosphate concentration and maximal abundance of red tide have been noted along the Roumanian Coast by various authors (Bodeanu & Usurelu, 1979; Mihnea, 1979). In the Seto Inland Sea, Japan, a 7 fold increase in red tide outbreaks between 1965 and 1976 was associated with increased levels of coastal nutrient enrichment (Prakash, 1987; Yanagi, 1988).

Thus, a regionally consistent and persistent pattern has emerged of a long term increased frequency of blooms associated with coastal nutrient enrichment (Smayda, 1990). This considerable evidence of significant changes in phytoplankton species occurrences, biomass and productivity, as well as shifts in predominance, occurring in regions as far apart as the North Sea and Hong Kong support the hypothesis that phytoplankton blooms are increasing in coastal waters on a global scale and that they are linked to long term increases in coastal nutrient levels. Anderson (1989) summed this up when he pointed out that the literature undeniably documents a global increase in the frequency, magnitude and geographic extent of coastal algal blooms and red tides over the past 2 decades and that

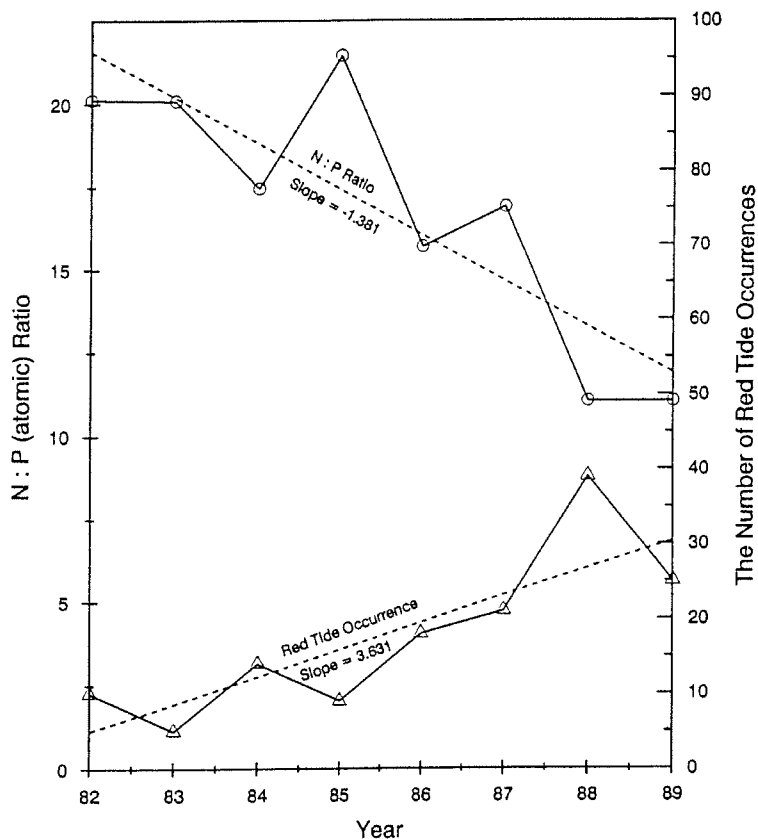


Figure 2. Variations in the N:P ratio versus red tide occurrences in inner Tolo Harbour during the years 1982–1989. (Original data courtesy of the Director, Environmental Protection Department, Government of Hong Kong).

there is very strong correlation between the number of red tides and the degree of coastal pollution.

Furthermore, the hypothesis that nutrient ratios are involved in increased blooms and species changes is, in our view, a viable one. Obviously, as Smayda (1989) put it, other factors will be involved in regulating bloom events, but nutrient ratios can be considered to be of major importance. At present unfortunately there are only limited data available in the literature to address this question for the marine phytoplankton, whereas much more is available for freshwater species (Sommer, 1987). Smayda (1989, 1990) has indicated how long term declines in the Si:N and Si:P ratios in the Baltic, North and Black Seas in response to nitrification, are accompanied by increased blooms of non siliceous phytoplanktonic groups. He presents evidence of such decreased Si:P ratios from the German Bight (Berg & Radach, 1985); Baltic Sea (Niemi & Aström, 1987); Gulf of Finland and Gulf of Bothnia (Pitkänen, 1978; Pitkänen & Malin, 1980); and the Belt

Sea (von Bodungen, 1986). He notes that significantly, not only have blooms of non-silica requiring groups increased during this same period, but they have even replaced the diatoms as the dominant biomass group in some areas.

Smayda (1990) has rehearsed the arguments for evaluating N and P ratios with Si, since this simplifies the evaluation into an issue of diatom blooms versus non diatom blooms versus ionic ratios. However, there is also evidence to link changes in the N:P ratio both with increases in blooms and with species changes. For example, Philips and Tanabe (1989) suggested that a shift in the N:P ratio of the loads entering marine coastal waters contributed to an alteration in species dominance in the phytoplankton population, with diatoms being gradually replaced by dinoflagellates and our data from Hong Kong indicate similar changes in species dominance and a consequent increase in red tides in relation to shifting N:P ratios.

Table 2. Changes in phytoplankton species composition in inner Tolo Harbour from 1978 to 1990

Year	Dominant Phytoplankton Species			
1981	Diatoms:	<i>Chaetoceros affine</i>		
		<i>C. costatum</i>		
		<i>C. curvisetum</i>		
		<i>Leptocylindrus danicus</i>		
		<i>L. minimus</i>		
		<i>Nitzschia delicatissima</i>		
		<i>Skeletonema costatum</i>		
1983	Diatoms:	<i>Chaetoceros costatum</i>		
		<i>Leptocylindrus danicus</i>		
		<i>L. minimus</i>		
		<i>Nitzschia delicatissima</i>		
		<i>N. longissima</i>		
		<i>N. seriata</i>		
		<i>Skeletonema costatum</i>		
1985	Diatoms:	<i>Leptocylindrus danicus</i>		
		<i>L. minimus</i>		
		<i>Nitzschia delicatissima</i>		
		<i>N. longissima</i>		
		<i>N. seriata</i>		
		<i>Skeletonema costatum</i>		
	Dinoflagellates:	<i>Prorocentrum sigmoides</i>		
		<i>P. triestinum</i>		
1988	Diatoms:	<i>Leptocylindrus danicus</i>		
		<i>L. minimus</i>		
		<i>Nitzschia delicatissima</i>		
		<i>N. seriata</i>		
		<i>Skeletonema costatum</i>		
			Diaoflagellates:	<i>Gonyaulax polygramma</i>
		<i>Gymnodinium nagasakiense</i>		
		<i>Noctiluca scintillans</i>		
		<i>Prorocentrum sigmoides</i>		
		<i>P. triestinum</i>		
1990	Diatoms:	<i>Leptocylindrus danicus</i>		
		<i>L. minimus</i>		
		<i>Nitzschia seriata</i>		
		<i>Skeletonema costatum</i>		
			Dinoflagellates:	<i>Gonyaulax polygramma</i>
				<i>Gymnodinium nagasakiense</i>
		<i>Noctiluca scintillans</i>		
		<i>Prorocentrum sigmoides</i>		
		<i>P. triestinum</i>		

Indeed, the results of our studies have given us an effective strategy for the management of red tides in Hong Kong. The control of P input **in addition** to the control of N input into Tolo Harbour was obviously required since, as a result of N control, the N:P ratio had fallen and so led to excessive red tides. Such falling N:P could possibly be used in other locations as a marker for predicting increased red tide occurrences and so for directing management actions.

Whether or not this 'local' strategy for red tide management in Hong Kong coastal waters can be applied globally (or indeed to oceanic as well as coastal waters) remains to be seen. What is clear, however, is that our results from Hong Kong clearly indicate that there has been an expansion of algal bloom problems; that these can be related to human activities and, in particular to the N:P ratio; and that increased international research efforts are needed to evaluate man's involvement in the possible global expansion of algal bloom problems and the relationship between nutrient ratios (particular N:P) and the appearance of blooms of many novel and harmful species.

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